

# CHEMICAL ABUNDANCE STUDY OF ONE RED GIANT STAR IN NGC 5694 : A GLOBULAR CLUSTER WITH DWARF SPHEROIDALS' CHEMICAL SIGNATURE?<sup>1</sup>

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## ABSTRACT

We report the abundance analysis of one red giant branch star in the metal-poor outer halo globular cluster NGC 5694. We obtain  $[Fe/H] = -1.93$ , based on the ionized lines, and our metallicity measurement is in good agreement with previous estimates. We find that  $[Ca+Ti/2Fe]$  and  $[Cu/Fe]$  of NGC 5694 are about 0.3 – 0.4 dex lower than other globular clusters with similar metallicities, but similar to some LMC clusters and stars in some dwarf spheroidal galaxies. Differences persist, however, in the abundances of neutron capture elements. The unique chemical abundance pattern and the large Galactocentric distance (30 kpc) and radial velocity ( $-138.6 \pm 1.0$  km sec $^{-1}$ ) indicate that NGC 5694 had an extragalactic origin.

*Subject headings:* Galaxy: halo — globular clusters: individual (NGC 5694) — stars: abundances

## 1. INTRODUCTION

The cold dark matter model for cosmology predicts a hierarchical formation mechanism for galaxies, with smaller units accreting to construct larger ones (e.g. Navarro, Frenk, &

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White 1995). Signs of merger fragments have been identified kinematically, especially the Sagittarius dwarf galaxy (Ibata et al. 1994), and probably the Monoceros Ring (Yanny et al. 2003). More substructure is predicted by the models but confirmations have proven elusive.

With the advent of large aperture telescopes, “chemical tagging” becomes a powerful technique to probe past merger histories. As Freeman & Bland-Hawthorn (2002) discussed, stars born in galaxies whose star formation histories differ from those that have created the bulk of the Galaxy’s stars may still be discernible in unusual element-to-iron ratios. For example, Cohen (2004) has found a compelling link between Palomar 12 and the Sagittarius dwarf, confirming the dynamical association found earlier by Dinescu et al. (2000). Venn et al. (2004) summarized the unusual abundance patterns found in the Galaxy’s dwarf spheroidal (dSph) galaxy neighbors, demonstrating that the bulk of the Galactic halo did not come from such surviving systems. Unique chemical abundance patterns of globular clusters and halo field stars may become a primary method to identify common star formation origins and histories.

NGC 5694 ( $\ell = 331.1$ ,  $b = +30.4$ ) is a metal-poor outer halo globular cluster lying far from the Sun (Harris 1975; Ortolani & Gratton 1990), as well as far from the Galactic center. Harris (1996) cites a Galactocentric distance of 29 kpc,  $E(B - V) = 0.09$ , and a large radial velocity,  $v_{\text{rad}} = -144.1 \text{ km sec}^{-1}$ . The large velocity and distance led Harris (1975) and Harris & Hesser (1976) to suggest that NGC 5694 has a hyperbolic orbit and it is not bound to our Galaxy, or that the Galaxy contains considerable additional mass beyond the solar orbit than simple model potentials indicate. We have used the analytical model of the Galactic gravitational potential from Allen & Santillan (1991) to estimate a lower limit to its apogalacticon distance. We first re-estimate the cluster’s distance, employing a mean horizontal branch  $V$  magnitude of 18.5 (Harris 1996) and the  $M_V$  vs. [Fe/H] relation of Cacciari (2003), finding  $R_{\text{GC}} = 30$  kpc. Based only on the radial velocity, the cluster travels over 100 kpc from the Galactic center. Any significant tangential velocity will likely increase this value further. Inspired by the outer halo nature of the cluster, we have begun a high-resolution spectroscopic study of one red giant branch star in the cluster. Our results suggest that NGC 5694 has a very distinctive elemental abundance pattern, similar in some respects to those of nearby dwarf spheroidal galaxies.

## 2. OBSERVATIONS, DATA REDUCTION AND ANALYSIS

We selected as our program star I-62 from the  $BV$  photometry by Harris (1975;  $V = 15.55$ ;  $B - V = 1.32$ ). The star has quality “A” 2MASS  $JK$  photometry (Cutri et al. 2000;  $K = 12.21$ ,  $J - K = 0.80$ ). The radial velocity measurements for red giant stars in NGC 5694

by Geisler et al (1995) using medium-resolution spectra at the Ca II infrared triplet showed that I-62 is a probable member of NGC 5694.

Our observations were carried out with the Magellan Clay Telescope using the Magellan Inamori Kyocera Echelle spectrograph (MIKE; Bernstein et al. 2003) on 6 July 2005. A  $0.^{\prime\prime}35$  slit was used providing a resolving power of  $\approx 50,000$  in the red with wavelength coverage from  $4950 \text{ \AA}$  to  $7250 \text{ \AA}$ , based on the full-with half maximum of the Th-Ar emission features. Four 2400s exposure were taken with this setting. We also obtained a spectrum of a fast rotating hot star to remove telluric absorption features. We used MIKE REDUX<sup>2</sup> to extract the spectra, and which effectively correct for the tilted slit.

Equivalent widths were measured mainly by direct integration of each line profile using the SPLOT task in IRAF ECHELLE package. We estimate our measurement error in equivalent width to be  $\pm 2$  to  $\pm 4 \text{ m\AA}$  from the size of noise features in the spectra and our ability to determine the proper continuum level.

For our line selection, laboratory oscillator strengths were adopted whenever possible, with supplemental solar oscillator strength values. We adopted the “Unsöld approximation” to account for van der Waals line broadening with no enhancement (Lee & Carney 2002; Lee, Carney, & Habgood 2005). We included the effects of hyperfine splitting for Mn, and both hyperfine and isotopic splitting for Cu and Ba. We neglected such corrections for La and Eu because the lines are very weak and the derived abundances are therefore insensitive to damping.

The initial temperature of the program star was estimated using its available  $BVK$  photometry and the empirical color-temperature and bolometric correction-color relations given by Alonso, Arribas, & Martinez-Roger (1999). To estimate the star’s relative to the Sun gravity using photometric data, we used  $\log g_{\odot} = 4.44$  in cgs units,  $M_{\text{bol},\odot} = 4.74$  mag, and  $T_{\text{eff},\odot} = 5777$  K. Using the estimated cluster distance and a stellar mass of  $0.8M_{\odot}$ , we found  $T_{\text{eff}} = 4135$  K and  $\log g = 0.6$ .

The abundance analysis was performed using the current version of the local thermodynamic equilibrium (LTE) line analysis program MOOG (Sneden 1973). For input model atmospheres, we interpolated Kurucz models using a program kindly supplied by A. McWilliam (2005, private communication). Adopting the photometric temperature and surface gravity as our initial values, we began by restricting the analysis to those Fe I lines with  $\log(W_{\lambda}/\lambda) \leq -5.2$  (i.e., for the linear part of the curve of growth), and comparing the abundances as a function of excitation potential. New model atmospheres were computed with a slightly

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different effective temperature until the slope of the  $\log n(\text{Fe I})$  versus excitation potential relation was zero to within the uncertainties. The stronger Fe I lines were then added and the microturbulent velocity  $v_{\text{turb}}$  altered until the  $\log n(\text{Fe I})$  versus  $\log(W_{\lambda}/\lambda)$  relation had no discernible slope. We obtained  $T_{\text{eff}} = 4200$  K and  $v_{\text{turb}} = 2.2 \text{ km sec}^{-1}$ .  $[\text{Fe}/\text{H}]$  was found to be  $-2.08 \pm 0.11$ , based on the neutral iron lines, and  $-1.93 \pm 0.07$ , based on the ionized lines. Since metal-poor stars have much weaker metal-absorption in the ultraviolet (UV), more non-local UV flux can penetrate from the deeper layers, which leads to over-ionization of neutral lines. Therefore Fe abundance derived from Fe I lines for metal-poor stars will always be underestimated, while Fe abundance derived from Fe II lines remains unaffected (Thévenin & Idiart 1999; Ivans et al. 2001). Our  $[\text{Fe}/\text{H}]$  values compare well with those estimated by other means by Zinn & West (1985;  $-1.92$ ) and its recalibration by Kraft & Ivans (2003), based on reliance on only the ionized lines for the calibrating clusters. Their derived  $[\text{Fe}/\text{H}]$  value, obtained using Kurucz models with convective overshoot turned on, as we have employed, was  $-2.04$ .

### 3. RESULTS AND DISCUSSION

#### 3.1. Radial Velocity

We measured the heliocentric radial velocity of the program star with respect to that of HD116713 using the IRAF FXCOR task and obtained  $-138.6 \pm 1.0 \text{ km sec}^{-1}$ . Our result is in good agreement with that of Geisler et al. (1995). Neglecting the three most deviant velocities, the remaining ten stars in Geisler's sample have a mean radial velocity of  $-140.7 \pm 2.4 \text{ km sec}^{-1}$  (the error is that of the mean). Our radial velocity measurement re-confirms that star I-62 is a member of NGC 5694.

#### 3.2. Elemental Abundances

Table 1 summarizes the elemental abundances of NGC 5694 I-62 using the photometric surface gravity and the spectroscopic temperature. The  $[\text{el}/\text{Fe}]$  ratios for neutral elements are estimated from  $[\text{el}/\text{H}]$  and  $[\text{Fe I}/\text{H}]$  ratios. The  $[\text{el}/\text{Fe}]$  for singly ionized elements (Ti II, Y II, Ba II, La II, and Eu II) are estimated from  $[\text{el}/\text{H}]$  and  $[\text{Fe II}/\text{H}]$  ratios. This procedure follows the study of M5 giants by Ivans et al. (2001), and has been employed in our prior work as well (Lee & Carney 2002; Lee, Carney, & Habgood 2005). See also Johnson et al. (2006) for a discussion of the challenges presented in comparing photometric and spectroscopic temperatures and gravities. In the Table,  $n$  is the number of lines used for the calculations

of mean elemental abundances and  $\sigma$  is the standard deviation per line. Systematic errors, such as in adopted  $gf$  values as a function of excitation potential, which could lead to systematically erroneous temperature estimates, are not included. A more detailed discussion of elemental abundances will be presented elsewhere in the future.

### 3.3. Comparisons with other Stellar Systems

Our results are based on the analysis of only one star, and the comparisons given below must be considered suggestive rather than definitive. But NGC 5694 appears to be unusual, almost unique, in its chemical abundance pattern and warrants further study.

NGC 5694 I-62 is deficient in  $\alpha$ -elements, in particular Ca and Ti, and the iron-peak element, Cu, compared with other globular clusters in our Galaxy. For [Ti/Fe], we adopt the unweighted average of [Ti I/Fe I] and [Ti II/Fe II]. Use of neutral titanium lines may suffer from NLTE effects, such as an over-ionization. However, the results from Ti II lines also yield lower titanium abundance scales in our program star, indicating that it is truly titanium deficient. In Figure 1, we show [Ca+Ti/2Fe] and [Cu/Fe] ratios as functions of [Fe/H]. We also show those of other globular clusters in our Galaxy (Pritzl et al. 2005; Simmerer et al. 2003), Large Magellanic Cloud (LMC) globular clusters (Johnson et al. 2006) and nearby dSph galaxies (Shetrone et al. 2003). The [Ca+Ti/2Fe] ratio of NGC 5694 I-62 is very similar to those of Palomar 12 and Terzan 7, which are associated with the Sagittarius dwarf galaxy (see Dinescu et al. 2000 regarding Palomar 12's association), and Ruprecht 106, which has been suggested to have been associated with the Magellanic Clouds (Lin & Richer 1992). On the other hand, other  $\alpha$ -elemental abundances, [Mg/Fe] and [Si/Fe], appears to be normal. The LMC cluster results from Johnson et al. (2005) also showed [Mg/Fe] and [Si/Fe] ratios similar to those of globular clusters in our Galaxy. Some iron-peak elemental abundances for NGC 5694 I-62, [Mn/Fe] and [Ni/Fe], appear to be normal (Sobeck et al. 2006; Gratton et al. 2004) relative to other clusters. However, the [Cu/Fe] ratio of NGC 5694 I-62 is  $\approx 0.4$  dex lower than those of globular clusters studied by Simmerer et al. (2003) at [Fe/H]  $\approx -2.0$  dex and the nearby dSphs studied by Shetrone et al. (2003). Some RGB stars in the Sculptor dSph galaxy<sup>3</sup> and LMC appear to have similar [Cu/Fe] ratios.

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<sup>3</sup>Note that Sculptor dSph is the oldest dSph galaxy studied by Shetrone et al. (2003). However, it appears to have several Gyr of active star formation and its star formation ended about 4 Gyr ago. On the other hand other dSphs have had even more extended periods of star formation, stopping only in the last 1 or 2 Gyr (Dolphin 2002; Tolstoy et al. 2003). As noted by the referee, proto-galactic fragments that disrupted very early in the first few Gyr would resemble only the oldest stellar populations in dSphs, which is not the dominant population in the dSphs because of their slow, but steady, star formation rates.

The  $\alpha$ -elements are predominantly synthesized during the SNe II shell-burning at the end of the lives of massive stars. Most Cu appears to be synthesized by an *s* process in massive stars. (The relative importance of SN Ia for Cu abundance remains uncertain, according to Clayton 2003.) Since NGC 5694 has a very old age (De Angeli et al. 2005), the contributions from SNe Ia are unlikely to be significant, since such events are not thought to appear until  $10^9$  or more years following the beginning of star formation. Further, the low [Cu/Fe] ratio of NGC 5694 cannot be understood by a metallicity-dependent yield from SNe Ia, which appears to be more important in more metal-rich regimes (e.g. McWilliam & Smecker-Hane 2005). One possible explanation would be that NGC 5694 formed from a proto-globular cluster cloud which was contaminated by relatively rare, massive SNe II (e.g. Tolstoy et al. 2003). This suggests that NGC 5694 formed in very different environment than the bulk of globular clusters in our Galaxy.

The neutron capture elements reveal even greater complexity. Venn et al. (2004) and Johnson et al. (2006) have noted the low abundances of  $[\alpha/\text{Fe}]$  and  $[\text{Cu}/\text{Fe}]$  for dSphs and LMC clusters compared to Galactic halo field and globular cluster stars, and Venn et al. (2004) drew special attention to  $[\text{Ba}/\text{Y}]$  as a significant difference as well. The LMC clusters studied by Johnson et al. (2006) do not share this trend, having solar  $[\text{Y}/\text{Fe}]$  ratios, as found in the Galactic halo, but somewhat enhanced  $[\text{Ba}/\text{Fe}]$ . NGC 5694 I-62 has a very low  $[\text{Y}/\text{Fe}]$  value, like the dwarf spheroidal galaxies, but its  $[\text{Ba}/\text{Fe}]$  ratio is lower, and lower than the LMC clusters as well.  $[\text{Eu}/\text{Fe}]$  is only slightly super-solar, resulting in a  $[\text{Ba}/\text{Eu}]$  ratio well below the LMC clusters or the dSphs.

In short, NGC 5694 is similar in some chemical abundance ratios to the LMC clusters and the dSphs, but a closer look at the neutron capture elements suggests significant differences.

Is NGC 5694 related to any of the existing dSphs? Kinematically the answer appears to be “no”. Lynden-Bell & Lynden-Bell (1994) introduced the concept of alignments of orbital poles, but did not identify NGC 5694 as related to any of the dwarf spheroidal galaxies. Majewski (1994) employed radial velocities in addition to positional data and drew a similar conclusion. Finally, space velocities have been employed by Palma et al. (2002) to compare the clusters’ motions, but, unfortunately, NGC 5694 still does not have a measured proper motion. We await such a measurement with keen interest, given that the estimated large apogalacticon distance and unique chemical abundances suggest that NGC 5694 formed independently of the bulk of the Galaxy, and was captured subsequently.

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Table 1. Elemental abundances.

Elem.	Sun			n	$\sigma$
		[Fe/H] <sub>I</sub>	[Fe/H] <sub>II</sub>		
Fe	7.52	[Fe/H] <sub>I</sub>	-2.08	40	0.11
		[Fe/H] <sub>II</sub>	-1.93	7	0.07
Mg	7.58	[Mg/Fe]	+0.15	2	0.03
Si	7.55	[Si/Fe]	+0.32	2	0.01
Ca	6.36	[Ca/Fe]	+0.00	7	0.06
Ti	4.99	[Ti/Fe] <sub>I</sub>	+0.00	10	0.11
		[Ti/Fe] <sub>II</sub>	-0.15	2	0.14
		[Ti/Fe] <sub>mean</sub>	-0.07	...	...
Mn	5.39	[Mn/Fe]	-0.38	2	0.09
Ni	6.52	[Ni/Fe]	-0.10	3	0.09
Cu	4.21	[Cu/Fe]	-1.05	1	...
Y	2.24	[Y/Fe] <sub>II</sub>	-0.58	2	0.02
Ba	2.13	[Ba/Fe] <sub>II</sub>	-0.52	3	0.09
La	1.22	[La/Fe] <sub>II</sub>	-0.26	1	...
Eu	0.51	[Eu/Fe] <sub>II</sub>	+0.18	2	0.11

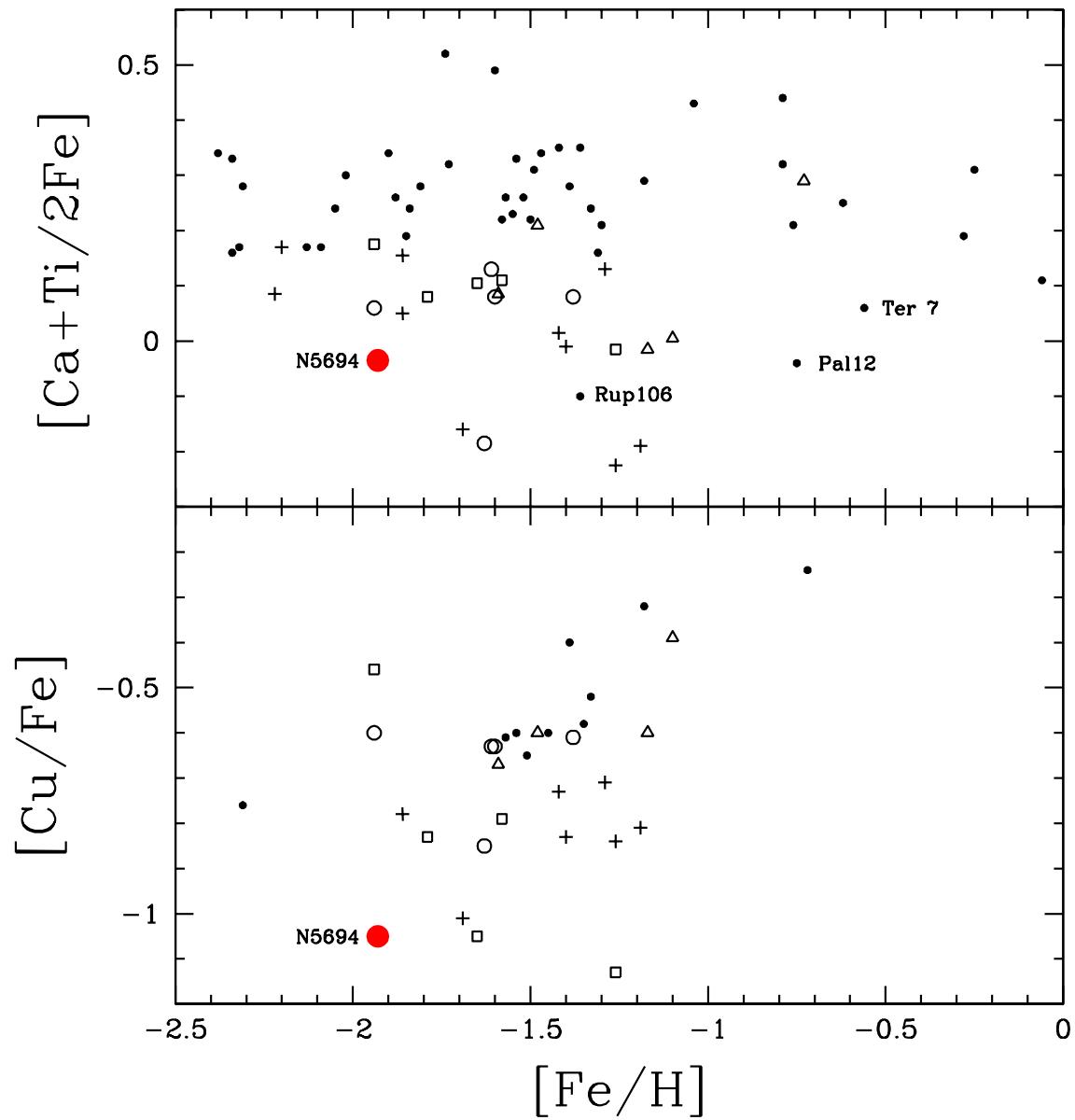


Fig. 1.—  $[Ca+Ti/2Fe]$  and  $[Cu/Fe]$  ratios as functions of  $[Fe/H]$ . Dots represent globular clusters in our Galaxy, open circles the Carina dSph, open triangles the Fornax dSph, open squares the Sculptor dSph, and crosses LMC clusters.

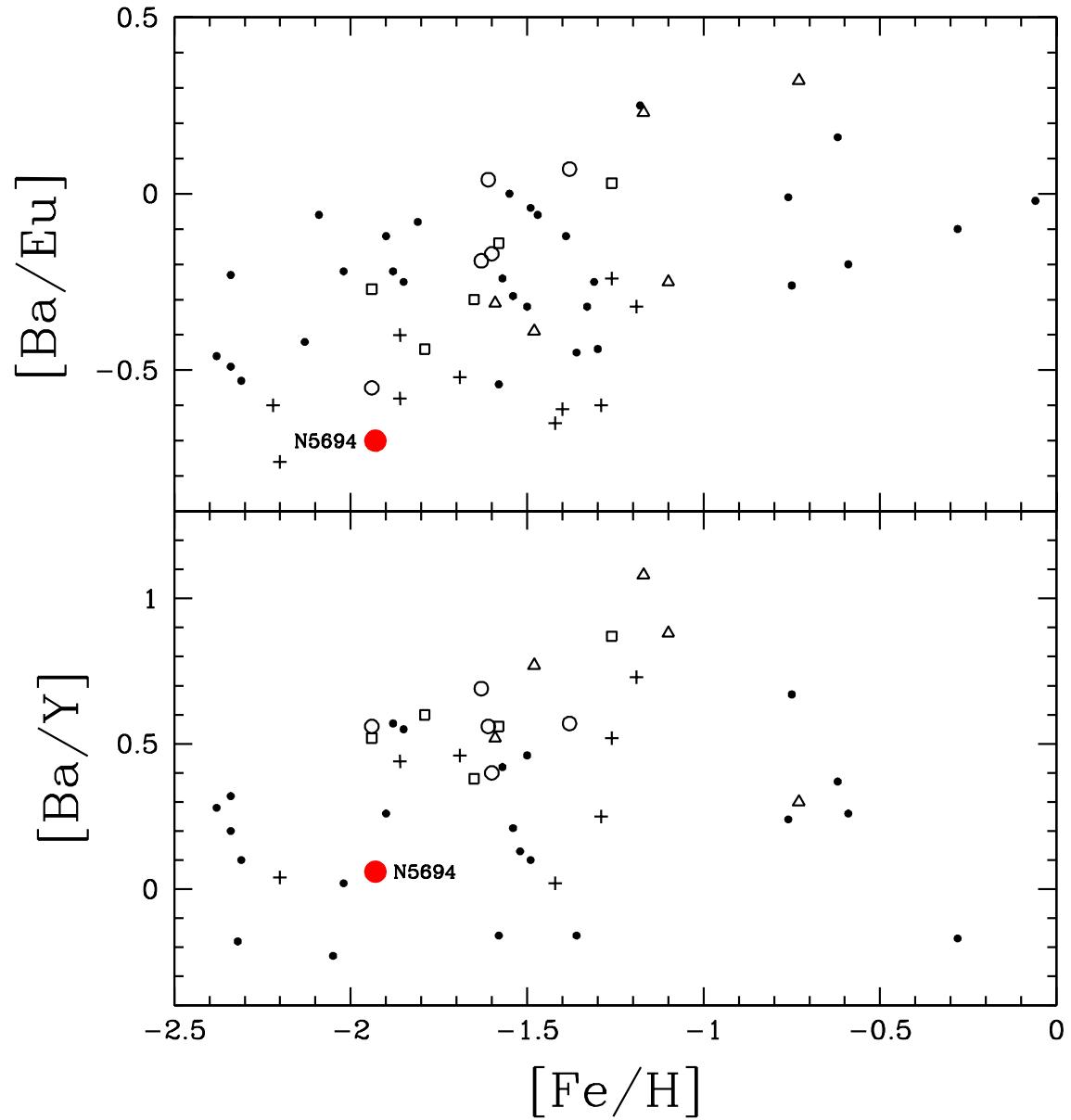


Fig. 2.—  $[Ba/Eu]$  and  $[Ba/Y]$  ratios as functions of  $[Fe/H]$ . We use the same symbols as in Figure 1.